

# Energetic Electron Transport in the Inner Magnetosphere During Geomagnetic Storms and Substorms: Final Research Report

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Prepared by

D. L. MCKENZIE and P. C. ANDERSON  
Space Science Applications Laboratory  
Laboratory Operations

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Engineering and Technology Group  
THE AEROSPACE CORPORATION  
El Segundo, CA 90245-4691

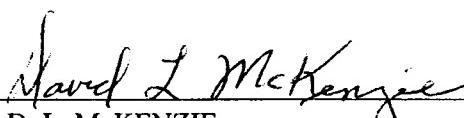
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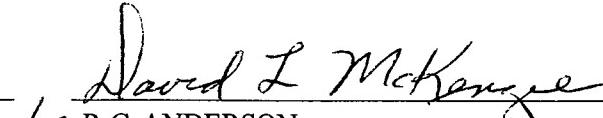
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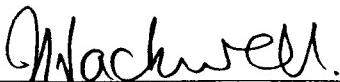


D. L. MCKENZIE  
Space Sciences Department  
Space Science Applications Laboratory



P. C. ANDERSON  
Space Sciences Department  
Space Science Applications Laboratory

Approved



J. A. HACKWELL, Director  
Space Sciences Department  
Space Science Applications Laboratory

**Note**

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## **Acknowledgment**

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## **Contents**

1. PIXIE (The Aerospace Corporation) Scientific Accomplishments .....	1
2. Publications 2002–2005 .....	5
2.1 First-Author Presentations 2002–2005 .....	5
References .....	7
Appendix—Energetic Electron Transport in the Inner Magnetosphere During Geomagnetic Storms and Substorms.....	9
Statement of Work.....	9
References for Appendix.....	12

## **Tables**

1. PIXIE (Aerospace) Refereed Publications by Fiscal Year.....	4
2. PIXIE (Aerospace) First-Author Presentations by Fiscal Year .....	4

## 1. PIXIE (The Aerospace Corporation) Scientific Accomplishments

Under NASA Grant NAG5-11696, we proposed "to examine the relationship of geomagnetic storms and substorms and the transport of energetic particles in the inner magnetosphere using measurements of the auroral X-ray emissions by PIXIE." The proposal statement of work is shown in the Appendix. The main thrust of the work has been large-scale auroral events, such as magnetic storms and substorms and the diffuse aurora.

*Anderson and Chen [2002a, 2002b]* showed that the auroral X-ray emissions associated with substorms show significant differences between isolated substorms and those occurring during geomagnetic storms. Using the on-line AE and  $Dst$  databases, the authors identified all periods of storms and substorms between September 1998 and August 1999 for which PIXIE data were available. During isolated substorms, at substorm onset, X-ray emissions are initially seen in the premidnight-to-midnight sector and then spread towards dawn. The emissions extend eastward beyond 12 MLT, with the most intense emissions occurring in the postdawn sector. The time scales for the appearance of X-ray emissions in the various morningside MLT sectors are consistent with the drift times of electrons, of energies that produce the photons observed by PIXIE, under the influence of a magnetospheric electric field inferred from ionospheric ion-drift measurements. During substorm recovery, emissions die away gradually at increasing MLT values with the last of the emissions, in the noon sector, disappearing several hours ( $\sim 3\text{--}4$ ) after substorm onset. During the stormtime substorms, onset-associated emissions are seen in the premidnight-to-midnight regions and spread toward dawn as in the isolated substorms. However, the emissions do not reach much beyond about 9–10 MLT, and very intense emissions are seen in the predawn MLT sectors. These intense predawn emissions are seen throughout the stormtime periods and are associated with significantly enhanced magnetospheric convection. There are brief reductions in intensity in the morningside emissions shortly after substorm onset consistent with a brief reduction in the cross-tail electric field, followed by intensification again in the predawn sector on a time scale consonant with drifting electrons under the influence of a magnetospheric electric field. The authors concluded that the differences between the temporal evolution and morphology of the auroral X-ray emissions during isolated and stormtime substorms are the result of pitch-angle scattering mechanisms whose MLT distribution and intensity are dependent on the strength of the magnetospheric electric field.

In an invited paper presented at the 6th International Conference on Substorms, *Anderson [2002]* discussed a broad range of PIXIE observations of auroral disturbances. These included observations during storms and substorms and identified disturbances associated with storms lacking the typical substorm signatures. During periods of prolonged enhanced convection such as occur during geomagnetic storms, large disturbances are observed that are distinct from substorms as determined from auroral emissions, geosynchronous particle observations, and geomagnetic field measurements. These disturbances include substantial auroral emissions in the morning sector with little activity in the premidnight sector. We concluded that they are associated with the earthward and downward drift of electrons caused by substantial cross-tail electric fields and magnetic field drift.

We continued work begun previously involving the comparison of the PIXIE X-ray emission patterns with the diffuse auroral model of *Chen and Schulz* [2001]. A paper [*Chen, et al.*, 2005] comparing emission patterns obtained from PIXIE and UVI during the main phase of the October 19, 1998 storm with the diffuse auroral model of *Chen and Schulz* [2002] has been accepted for publication in *Journal of Geophysical Research*. Preliminary results of this study were reported at the 2002 Fall Meeting of the AGU [*McKenzie et al.*, 2002] and at the Polar Spacecraft Science Working Group Workshop in November, 2003 [*Chen et al.*, 2003]. We obtained the storm-time plasma sheet electron distribution by mapping LANL geosynchronous data outward to an equatorial neutral line at  $12.8 R_E$ , which was also the boundary of the model, and tracing bounce-averaged drifts of plasma sheet electrons in the limit of strong pitch-angle diffusion. We used a magnetospheric convection electric field created by mapping an analytical expansion of the AMIE (Assimilative Model of Ionospheric Electrodynamics) ionospheric potential along magnetic field lines from the ionosphere. Using the simulation results, we mapped stormtime phase-space distributions along particle drift shells, taking into account loss due to precipitation. We considered two models of electron scattering: the limit of strong scattering everywhere and MLT-dependent scattering that is less than everywhere strong in the plasma sheet. The MLT-dependent scattering distributions were motivated by the statistical SCATHA wave observations of *Roeder and Koons* [1989] and the results of *Anderson et al.* [2000a, 2000b] and *Anderson* [2002]. We optimized the MLT dependence to fit the auroral images, with a maximum at 04:00 MLT and a minimum at 16:00 MLT. From the phase-space distributions thus obtained, we calculated the precipitating electron energy flux into the atmosphere and compared the results with the X-ray fluxes measured by PIXIE and the precipitating energy fluxes derived from UVI observations. For the comparison with the PIXIE images, we weighted our simulated electron flux by the bremsstrahlung X-ray production curve to obtain simulated X-ray fluxes.

The comparisons reveal that pitch-angle scattering plays a crucial role in determining the spatial distribution of the precipitating electron energy flux. The simulated stormtime energy flux with strong diffusion tends to be much more intense in the evening sector and much weaker near dawn than what is statistically observed. Under everywhere-strong pitch-angle scattering, very intense precipitation occurs in a relatively small MLT range, where the drift times from the plasma sheet are of the same order as the electron lifetime against strong diffusion. This results in electron fluxes, and X-ray emissions, that are too strong in the evening sector. On the other hand, the MLT-dependent scattering model produces a simulated diffuse aurora that is in good agreement with results inferred from UVI data. The detailed agreement with the PIXIE X-ray intensities is not as good, perhaps because the interpretation of the X-ray images to extract energy flux is more complex than obtaining the same information from UV images. The study suggests that wave scattering is weak in the post-dusk sector and strong in the morning sector, which is in general agreement with stormtime wave observations.

An unusual event on August 27, 1998 showed intense X-ray emissions in the afternoon sector, where they are rarely seen. Intense afternoon emissions were seen intermittently in the PIXIE front chamber ( $\sim 2\text{--}10$  keV X rays) over a period of  $\sim 3$ -hours; in the back chamber ( $\sim 10\text{--}50$  keV), a very intense spot was observed for about 40 min near 1600 MLT. Fortunately, the Solar, Anomalous, Magnetospheric Particle Explorer (SAMPEX) satellite passed through the conjugate footprints of the magnetic field lines threading the location of the bright afternoon spot. There were also several passes of the Defense Meteorological Satellite Program (DMSP) satellites through the afternoon sector during the time of the PIXIE observations. DMSP provides measurements of the energetic electron precipitation up to  $\sim 32$  keV, while SAMPEX provides measurements of the energetic electron precipitation up to

several MeV. The DMSP observations show energy spectra peaking near 10 keV, indicating that the X rays seen in the PIXIE front chamber were produced by electrons with energies less than about 20 keV. However, the SAMPEX observations indicate that the emissions seen in the back chamber were produced by electrons in the MeV range. The fluxes in the MeV range were very intense and the spectra were very hard, indicating that two populations of electrons produced the X rays observed by PIXIE. The study of this event has the aim of identifying the possible sources of the energetic electron populations generating the observed X-ray emissions. Work on this study under the present grant stopped when co-investigator Dr. Phillip Anderson left The Aerospace Corporation for the University of Texas at Dallas in the spring of 2004, but Dr. Anderson intends to complete the work with other funding sources.

We are collaborating with colleagues on an investigation of the use of the data from the IRIS and HAARP riometer arrays in deriving information on the temporal and energy distribution of high-energy electron precipitation in the auroral zone. These facilities are ideal for this study in that they can provide a spatial measurement similar to the spatial resolution of the PIXIE instrument. Imaging riometers respond to changes in the absorption of cosmic radio noise in the ionosphere and have a similar energy response to PIXIE in that the energy dependence of the absorption is nonlinear and increases with precipitating electron energy. Initial results show that often the X-ray flux is very well correlated with the measured absorption. At other times, the temporal variation is nearly identical, but the ratio of the measured X-ray flux and absorption varies significantly. This observation suggests that spectral information can be derived by comparing the PIXIE and riometer data. The inclusion of imaging data from UVI and particle measurements from the DMSP and SAMPEX satellites will provide additional information of the energy distribution of the precipitating electrons. We are continuing to pursue this work at a low level both at The Aerospace Corporation, under the present grant, and at the University of Texas at Dallas.

The history of PIXIE (Aerospace) publications and first-author presentations is displayed in Tables 1 and 2. The tables are followed by lists of publications and first-author presentations under NASA Grant NAG5-111696.

Table 1. PIXIE (Aerospace) Refereed Publications by Fiscal Year

Fiscal Year	First-Author Publications	Co-Author Publications
1992		
1993	1	
1994		
1995		1
1996		
1997		2
1998	1	1
1999		2
2000	1	2
2001	3	1
2002	1	
2003		
2004 (Submitted)		
2004 (Accepted)	1	
2004 (Published)		

Note: First- and co-authored publications are counted as first-author only.

Table 2. PIXIE (Aerospace) First-Author Presentations by Fiscal Year

Year	Number of Presentations
1992	1
1993	
1994	
1995	
1996	
1997	2
1998	1
1999	5
2000	2
2001	3
2002	3
2003	1
2004	

## **2. Publications 2002–2005**

Anderson, P. C., and M. W. Chen, Examination of the storm/substorm relationship using global auroral X-Ray images, *J. Geophys. Res.*, 107 (A3), 10.1029/2001JA009184, 2002.

Chen, Margaret W., Michael Schulz, Phillip C. Anderson, Gang Lu, G. Germany, and Martin Wuest, Stormtime distributions of diffuse auroral electron energy and X-ray flux: Comparison of drift-loss simulations with observations, *J. Geophys. Res.*, 2005 (accepted for publication).

### **2.1 First-Author Presentations 2002–2005**

Anderson, P. C., Global X-ray Observations of Auroral Disturbances, 6th International Conference on Substorms, University of Washington, Seattle, WA., 2002.

Anderson, P. C., and M. W. Chen, Examination of the storm/substorm relationship using global auroral x-ray images, 34th COSPAR Scientific Assembly, Houston, TX., 2002.

Chen, M. W., M. Schulz, P. C. Anderson, G. Lu, G. Germany, M. Wuest, and D. L. McKenzie, The Storm-time Diffuse Aurora: Comparisons of Simulations and Observations, 2003 Polar Spacecraft Science Working Group Workshop, Iowa City, Iowa, 2003.

McKenzie, D L, M. W., Chen, M Schulz, P. C. Anderson, G. Lu, M. P. Wuest, Simulations of Storm-time Diffuse Aurora Using AMIE Electric Field and Flux-Dependent Electron Scattering Model, Fall 2002 AGU, San Francisco, CA., 2002.

## References

- Anderson, P. C., Global X-ray Observations of Auroral Disturbances, 6th International Conference on Substorms, University of Washington, Seattle, WA., 2002.
- Anderson, P. C., and M. W. Chen, Examination of the storm/substorm relationship using global auroral X-ray images, *J. Geophys. Res.*, **107** (A3), 10.1029/2001JA009184, 2002a.
- Anderson, P. C., and M. W. Chen, Examination of the storm/substorm relationship using global auroral X-ray images, 34th COSPAR Scientific Assembly, Houston, TX., 2002b.
- Anderson, P. C., D. L. McKenzie, M. W. Chen, M. J. Brittnacher, M. Hairston, and M. F. Thomsen, Global storm time auroral X-ray morphology and timing and comparison with UV measurements, *J. Geophys. Res.*, **107**, 15,757, 2000a.
- Anderson, P. C., D. L. McKenzie, L. R. Lyons, and M. Hairston Global X-ray Observations of Magnetospheric Convection-Driven Auroral Disturbances, *Geophys. Res. Lett.*, **27**, 3233, 2000b.
- Chen, M. W., and M. Schulz, Simulations of storm time diffuse aurora with plasma sheet electrons in strong pitch angle diffusion, *J. Geophys. Res.*, **106**, 1873-1886, 2001.
- Chen, M. W., and M. Schulz, Simulations of stormtime diffuse aurora with plasmashell electrons in pitch-angle diffusion less than everywhere strong, *J. Geophys. Res.*, **106**, 28949, 2002.
- Chen, Margaret W., Michael Schulz, Phillip C. Anderson, Gang Lu, G. Germany, and Martin Wuest, Stormtime distributions of diffuse auroral electron energy and X-ray flux: Comparison of drift-loss simulations with observations, *J. Geophys. Res.*, 2005 (accepted for publication).
- Chen, M. W., M. Schulz, P. C. Anderson, G. Lu, G. Germany, M. Wuest, and D. L. McKenzie, The Storm-time Diffuse Aurora: Comparisons of Simulations and Observations, 2003 Polar Spacecraft Science Working Group Workshop, Iowa City, Iowa, 2003.
- McKenzie, D L, M. W., Chen, M Schulz, P. C. Anderson, G. Lu, M. P. Wuest, Simulations of Stormtime Diffuse Aurora Using AMIE Electric Field and Flux-Dependent Electron Scattering Model, Fall 2002 AGU, San Francisco, CA., 2002.
- Roeder, J. L., and H. C. Koons, A survey of electron cyclotron waves in the magnetosphere and diffuse auroral electron precipitation, *J. Geophys. Res.*, **94**, 2529, 1989.

## **Appendix—Energetic Electron Transport in the Inner Magnetosphere During Geomagnetic Storms and Substorms**

### **Statement of Work**

We propose to examine the relationship of geomagnetic storms and substorms and the transport of energetic particles in the inner magnetosphere using measurements of the auroral X-ray emissions by PIXIE. PIXIE provides a global view of the auroral oval for the extended periods of time required to study stormtime phenomena. Its unique energy response and global view allow separation of stormtime particle transport driven by strong magnetospheric electric fields from substorm particle transport driven by magnetic-field dipolarization and subsequent particle injection.

The view of the relationship between geomagnetic storms and substorms has undergone a transformation in recent years. *Chapman* [1962] proposed that storms comprise a collection of substorms, and that by understanding the dynamics of individual substorm energy injection, one could understand the entire storm process. Recently available global auroral images acquired over the extended periods (several hours) required to study storm development fully have shown that the relationship between storms and substorms is more complex than that proposed by *Chapman* [1962]. *Anderson et al.* [2000a; 2000b] presented UV and X-ray images showing long periods (hours) of significant morningside activity associated with strong stormtime magnetospheric convection but lacking the intense premidnight emissions associated with substorms. Substorm activity was observed during the storms, but the substorm-generated emissions were relatively short-lived, and the associated precipitating electrons appeared to contribute less to the overall energy input from the storm than the strong convection-associated precipitation. Indeed, there are indications that the magnetospheric convection strength actually drops with initiation of a substorm.

The relative importance of substorms in releasing stored magnetospheric energy during storms and injecting particles into the inner magnetosphere and the ring current is currently hotly debated. The distribution of particles in the inner magnetosphere is often inferred from measurements of the precipitating auroral particles. Thus, the global distributions of the characteristics of energetic precipitating particles during storms and substorms are extremely important inputs to any description or model of the geospace environment and the Sun-Earth connection. We propose to use PIXIE observations and modeling of the transport of energetic electrons to examine the relationship between storms and substorms.

The proposed work will consist of three phases over a three-year period. In the first year, we will identify all geomagnetic storms and isolated substorms occurring between May 1997 (when the PIXIE duty cycle was increased first to ~50%, and later to ~80% of the time when *Polar* is outside the radiation belts) and the present using the *Dst* and *AE* geomagnetic field indices. The list of events will be cross-correlated with the PIXIE observation periods, and the relevant PIXIE data will be collected and processed. Ancillary data will be collected from the *Defense Meteorological Satellite Program* (*DMSP*) satellites, the *Solar Anomalous-Component Magnetospheric Particle Explorer* (*SAM*-

*PEX*), and the *Los Alamos National Laboratory (LANL)* geosynchronous spacecraft. The *DMSP* spacecraft fly in sun-synchronous orbits at ~840 km altitude and provide the ionospheric electric field pattern from which the cross-polar-cap-potential drop ( $\Delta\Psi_{PC}$ ) is calculated, and the magnetospheric electric field strength is inferred. They also measure the precipitating energetic electrons and ions in the energy range from ~30 eV to 32 keV. *SAMPEX* orbits at an altitude of ~600 km with an orbital inclination of 82° and has several instruments measuring energetic particles between ~25 keV and several MeV; of primary interest are the integral electron measurements above 25 keV provided by the Low-Energy Ion Analyzer (LEICA). The *LANL* instruments provide measurements of energetic particles from ~1 eV to several MeV; of primary interest are the electron measurements from the Magnetospheric Plasma Analyzer (MPA) from ~1 eV to 40 keV and the Synchronous Orbit Particle Analyzer (SOPA) from 30 keV to 200 keV.

In the second year, periods of substorm activity during the storms will be identified, and the characteristics of both the stormtime substorms and the isolated substorms will be determined, including the times of onset and recovery and the temporal evolution and spatial distribution of the emissions and energetic particles. In a limited study of the characteristics of stormtime substorms and isolated substorms discussed in the results section of this proposal, *Anderson and Chen* [2002] found significant differences, primarily in the MLT extent of the X-ray emissions. The differences were attributed to the result of pitch-angle scattering mechanisms whose MLT distribution and intensity were dependent on the strength of the magnetospheric electric field. We will expand considerably on the *Anderson and Chen* [2002] work, comparing the stormtime substorms and the isolated substorms and categorizing in detail the differences.

In a diffuse aurora model, *Chen and Schulz* [2001a] considered strong diffusion everywhere in their stormtime simulations and found that the precipitating electron energy flux peaked near midnight throughout the quiescent, main, and recovery phases of a storm, in contrast to the results of *Anderson et al.* [2000a; 2000b]. This was because the transport time of electrons from the nightside neutral line to midnight, where the electron flux peaked, was comparable to lifetimes against strong diffusion. Using an MLT-dependent pitch-angle scattering that was less than strong everywhere, *Chen and Schulz* [2002] were able to reproduce stormtime precipitating electron distributions that were qualitatively similar to stormtime auroral emissions patterns measured by PIXIE.

The *SAMPEX* measurements will provide some insight into the MLT distributions of the pitch-angle distributions. In 1997 and 1998, the spacecraft was spinning, providing pitch angle distributions of the electrons above 25 keV. We will identify the isotropy of the electron distributions using the pancake index, defined as the ratio of the fluxes at 90° pitch angle and ~70° pitch angle (see for instance *Wrenn et al.* [1979] and *Meredith et al.* [1999]). These distributions will be tabulated with respect to MLT, stormtime phase,  $\Delta\Psi_{PC}$ , time delay from substorm onset, and PIXIE emission intensity to provide the MLT distribution and temporal evolution of the pitch-angle scattering.

In *Anderson and Chen* [2002], the temporal evolution of the MLT distributions of the electrons and the electron drift times were calculated using the diffuse aurora model of *Chen and Schulz* [2001a] and  $\Delta\Psi_{PC}$  values inferred from the *DMSP* ion drift measurements. The results were found to be consistent with PIXIE X-ray and *DMSP* particle measurements. Modification of the *Chen and Schulz* [2001a] diffuse aurora model continues with NSF support; we will be testing the modifications continuously during the study period, simulating the storms and substorms identified and comparing the

results with the PIXIE data. We are currently simulating portions of the October 19, 1998 storm reported in *Anderson et al.* [2000a; 2000b], and a paper is in preparation for submission to the special *JGR* issue entitled "Causes of the Aurora."

In the final year, we will investigate the evolution of the particle distributions in the inner magnetosphere during storms and ascertain the importance of substorms in injecting particles into the inner magnetosphere. We will use the times of stormtime substorm onset and perform a superposed epoch and regression analysis with the *Dst* index to investigate the importance of substorms in the evolution of the ring current. We will also identify periods of strong convection not associated with substorms (see *Anderson et al.* [2000a; 2000b]) and compare with changes in *Dst* to ascertain the importance of magnetospheric convection in the injection of particles into the inner magnetosphere and the ring current. Finally, given the times of the beginning and end of the storm main phase and the time periods of substorm activity within the storm, we will attempt to calculate the fraction of the total energy released in the auroral ionosphere by precipitating electrons (in the energy range producing X-ray emissions measured by PIXIE) associated with substorms and those associated with stormtime convection.

We also mention two ongoing studies we are performing using the PIXIE database. On September 24, 1998, a pressure pulse associated with a coronal mass ejection (CME) encountered the Earth's magnetopause near 23:40 UT. Shortly after, within less than 2 min, almost the entire auroral oval lit up in X rays, with emissions extending past noon in the afternoon sector, something rarely seen in PIXIE images. The dayside emissions lasted for only a few minutes before dying away with the inception of substorm activity in the premidnight sector. Magnetometer measurements, measurements at the IRIS riometer array, and PIXIE measurements all show a different timing associated with the pressure pulse. We are analyzing the energy distribution of the precipitating particles as inferred from PIXIE and the temporal evolution of the global emission patterns in an effort to understand the particle energization and injection mechanisms associated with pressure pulses. PIXIE can provide the event onset times and the temporal evolution of the emissions to a resolution of ~30 s and the energy distributions with a time resolution of a few minutes. We note that this is during a period when both chambers of the instrument were operating at maximum duty cycle, thus enabling better determination of the precipitating electron distributions.

Another study involves investigation of tri-spectral images of a substorm surge. *Anderson et al.* [2000a] showed X-ray and UV images of a geomagnetic storm and discussed the importance of multi-spectral imaging. The only tri-spectral study to date was reported by *Cummer et al.* [2000]; however, the data were limited, particularly as multi-wavelength data were unavailable from UVI. On February 18, 1999, VIS, UVI, and PIXIE were all imaging the premidnight sector during the expansion phase of a substorm. This was a unique event in that the UVI and VIS instruments were taking images at all available wavelengths, and the substorm surge was in view throughout the expansion phase by all three imagers. We are currently analyzing this event and investigating the validity of the assumed Gaussian spectra used in the energy analysis by the imagers. We will use the results to study the acceleration processes associated with the substorm surge.

## References for Appendix

- Anderson, P. C., D. L. McKenzie, M. W. Chen, M. J. Brittnacher, M. Hairston, and M. F. Thomsen, Global storm time auroral X-ray morphology and timing and comparison with UV measurements, *J. Geophys. Res.*, **107**, 15,757, 2000a.
- Anderson, P. C., D. L. McKenzie, L. R. Lyons, and M. Hairston, Global X-ray observations of magnetospheric convection-driven auroral disturbances, *Geophys. Res. Lett.*, **27**, 3233, 2000b.
- Anderson, P. C., and M. W. Chen, Examination of the Storm/Substorm Relationship Using Global Auroral X-Ray Images, submitted to *J. Geophys. Res.*, 2002.
- Chen, M. W., and M. Schulz, Simulations of stormtime diffuse aurora with plasmasheet electrons in strong pitch-angle diffusion, *J. Geophys. Res.*, **106**, 1873, 2001a.
- Chen, M. W., and M. Schulz, Simulations of stormtime diffuse aurora with plasmasheet electrons in pitch-angle diffusion less than everywhere strong, *J. Geophys. Res.*, in press, 2001b.
- Chapman, S., Earth storms: retrospect and prospect, *J. Phys. Soc. Jpn.*, **17**, 6, 1962
- Cummer, S.A., R.R. Vondrak, N. Ostgaard, J. Stadsnes, Global multispectral auroral imaging of an isolated substorm, *Geophys. Res. Lett.*, **27**, 637, 2000
- Meredith, N. P., A. D. Johnstone, S. Szita, R. B. Thorne, and R. R. Anderson, "Pancake" electron distributions in the outer radiation belts, *J. Geophys. Res.*, **104**, 12431, 1999.
- Wrenn, G. L., J. F. E. Johnson, and J. J. Sojka, Stable 'pancake' distribution of low energy electron in the plasma trough, *Nature*, **279**, 512, 1979.